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RESEARCH GROUP

Report

THE ECONOMIC GENERATION OF POWER FROM THERMONUCLEAR FUSION

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THE ECONOMIC GENERATION OF POWER FROM THERMONUCLEAR FUSION

by

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ABSTRACT

Plasma confinement systems are examined as to their potential for satisfying plasma power balance requirements for electrical power generation from the D-T fusion reaction. From this analysis a steady state toroidal system is taken as a model and engineering parameters are identified defining

(i) the form and size of an economic fusion reactor;

(ii) the plasma confinement parameters which must be satisfied.

Capital and generation costs for a power station based on this model are estimated and it is shown that the generation costs compare favourably with those from other possible energy sources. A similar study of a D-D reactor indicates that this could provide an economic power source though the confinement parameters are more stringent. These economic studies are used to identify technological problems requiring investigation.

U.K.A.E.A. Research Group,
Culham Laboratory,
Abingdon,
Berks.

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TABLES

SYMBOLS

α	Containment parameter $(= \tau/\tau_B)$	
B	Magnetic field; outside plasma - assumed uniform	
β	Ratio of plasma to magnetic pressure	
Δ	Tritium breeding gain per fusion	
ζ	Bremsstrahlung correction factor	
ε	Power reinjection fraction	
f	Burn up - fraction of fuel consumed	
k	Boltzmann constant	kT is given in keV
T	Temperature	
L	Fractional tritium loss	
n	Number density of electrons	
η	Efficiency – η_T Thermal efficiency η_I Injector efficiency	
P_b	Bremsstrahlung radiation power	
P_c	Cyclotron radiation power	
P_n	Nuclear power per unit volume	
P_T	Reactor rating	
P_w	Reactor output/unit wall area	
Q_c	Energy of charged fusion reaction products per fusion cycle. 3·52 MeV for D-T cycle. 26·7 MeV for D-D cycle.	
Q_T	Total reaction energy per fusion cycle. For D-T cycle (1D and 1T fusion) equals fusion reaction energy (17·6 MeV) plus Li^6 capture energy (4·8 MeV). For D-D cycle (6D fusion) equals fusion reaction energy (43·2 MeV) plus Na capture energy (25·2 MeV)	
R	Major radius of toroid	
r_c	Toroid aperture radius - see Fig.3	
r_p	Plasma radius	
r_w	Vacuum wall radius	
s	Winding radial thickness	
$\langle\sigma v\rangle$	Reaction rate parameter	
t	Blanket radial thickness	
τ	Containment time	
τ_B	Bohm diffusion time	
y	Ratio plasma radius to wall radius	

1. INTRODUCTION

1. Throughout the world, controlled fusion research programmes[1,2] are in the main directed towards stabilising a plasma confined by a magnetic field. The aim is to confine a plasma of hydrogen isotopes at temperatures of about 100 million ^{o}K long enough for exoenergetic fusion reactions between the nuclei to produce a net power gain. For the study reported here, we assume that this physics problem can be solved. We survey the current experimental systems used for confining plasma and select the most promising for an examination of the engineering and costing of the ultimate goal of fusion research - the economic generation of power.

2. We therefore postulate an electricity generating station which, though otherwise of conventional form, utilises a reacting plasma of deuterium and tritium contained by magnetic fields as its energy source. This D-T plasma is surrounded by a nuclear energy converter or 'blanket' in which the fusion energy is abstracted from the reactor. In this same blanket, sufficient tritium is produced by the Li(n,t) reaction to replace that consumed by the fusion process in the plasma, so that apart from the initial charge the fuel consists of deuterium and lithium, i.e. the 'D-T-Li' system. We determine the size and shape of our conceptual fusion reactor from comparatively simple engineering (and economic) arguments and further we derive the necessary plasma containment parameters for an economic power generating fusion reactor. We estimate the capital and unit generation cost for a D-T fusion power station. We include a brief study of other possible reaction cycles, for example, D-D-Na.

3. The analysis is based on scanty information available for some portions of the system and is therefore somewhat speculative. There are revealed a number of technological problems which are common to present concepts of fusion reactor power stations. These problems and possible solutions are discussed.

4. Within these limitations we show that the cost of fusion power could be in the range 0·23 - 0·25 pence per kW (at 1967 prices).

2. CURRENT APPROACHES TO PLASMA CONFINEMENT

5. Almost without exception, current laboratory fusion experiments rely on the magnetic confinement of plasma in various magnetic field configurations. The present approaches can be divided into five classes:

(i) Mirror Machines

The power balance from fusion reactions in a mirror machine has been extensively studied[3,4,5]. The conclusions reached by the different authors depend critically on their estimates of the scattering losses, but even in the most favourable analysis a net power output is achieved by only a small margin. If all the energy associated with the classical scattering loss through the mirrors can be recovered only through a conventional thermal cycle, it seems most unlikely that a mirror machine could satisfy the conditions for an economic fusion reactor. The invention of techniques for reducing the loss or for efficient utilisation of the lost charged particle energy would change the situation.

(ii) Pulsed Systems*

Plasma containment experiments commonly employ pulsed magnetic fields derived from capacitor banks; θ-pinch and Z-pinch geometries are examples. In Appendix I we derive in a general way the capacitor bank component of the capital cost of such a reactor. It turns out to be so expensive that we are forced to conclude that a very much cheaper form of energy storage is a prerequisite of an economic pulsed fusion reactor.

(iii) Steady-State Closed-Line Systems

Although the plasma containment achieved experimentally is in general no better in closed-line systems than in open-ended ones, in principle the former do not suffer from the limitations imposed by irreducible end losses. A practical fusion reactor requires a cross-field diffusion coefficient about 10^5 times less than the simple classical value. Moreover, in these systems the charged reaction products can also be contained, providing a heating mechanism for new fuel and replenishing energy losses from the plasma.

(iv) Astron

The special feature of this closed-line configuration is that the confining magnetic field is produced mainly by a layer of relativistic electrons. A 5-year project aimed at significant plasma confinement experiments in 1970-71 has been launched, and will be a crucial test of this approach[6]. An assessment of its reactor potential has been made[7].

(v) Others

Alternative approaches to fusion power not relying on the magnetic confinement of plasma have been suggested from time to time. These include the muon catalysis of fusion reactors[8], colliding macrons[9], and the inertial containment of plasma generated by converging shock waves[10] or laser-produced light[11]. At present none of these appear to offer the possibility of net gain from a reactor of reasonable dimensions.

3. CONCEPTUAL D-T REACTOR

6. The above considerations led us to choose, for the purpose of this study, a conceptual fusion reactor containing a plasma in steady-state toroidal geometry fuelled with a 50/50 mixture of deuterium and tritium. We assume adequate control of plasma stability and equilibrium. The conceptual design which emerges is illustrated in Figs.1 and 2. We have used data from the work of Rose and his students[12,13] for the tritium breeding blanket.

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*Pulsed systems are here defined as those in which the pulse length is of the same order as the particle containment time: steady-state considerations apply to systems employing much longer pulses, with economic penalties arising from the reduced utilisation factor and the capital cost of auxiliary pulsing equipment.

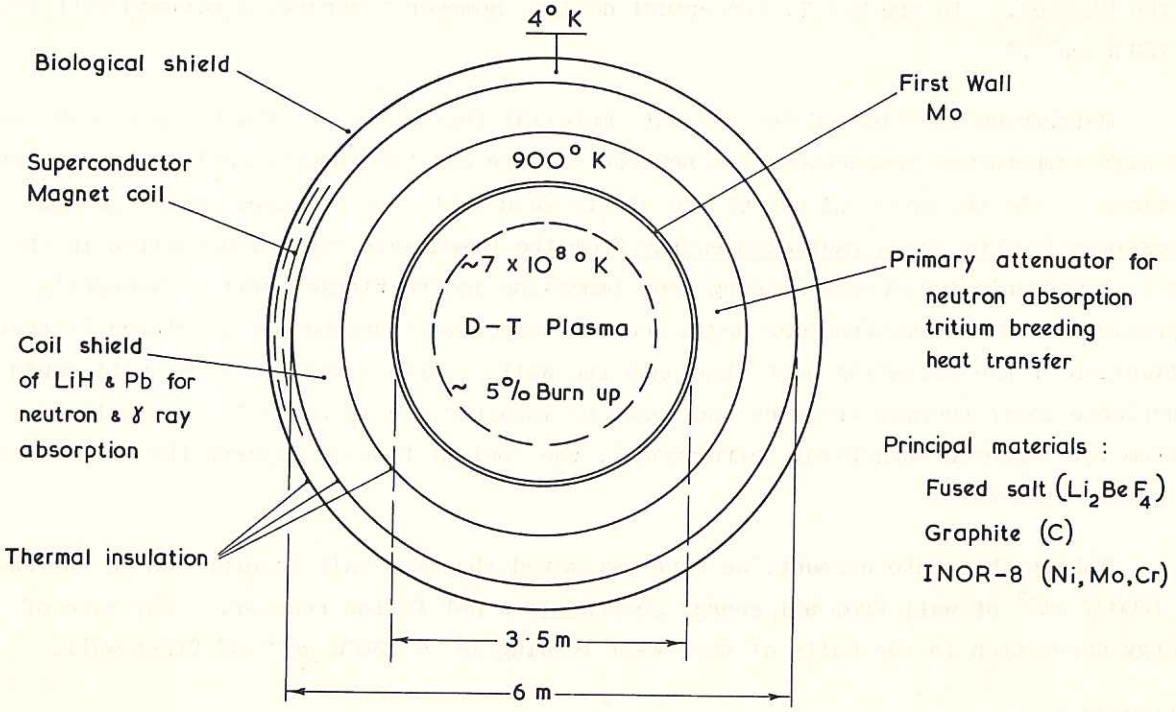

Fig. 1
(CLM-R85)
Conceptual design cross section of D-T Reactor - blanket data after Homeyer$^{(13)}$.

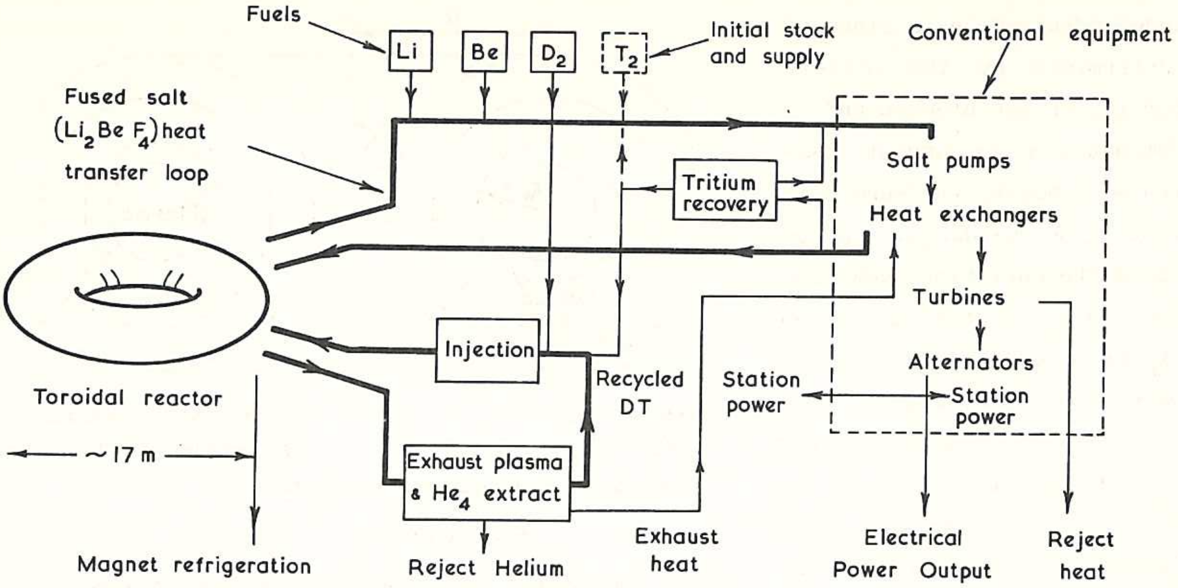

Fig. 2
(CLM-R85)
Functional diagram of D-T Fusion Reactor Generating Station

Wall Loading

7. We define wall loading, P_W (W cm^{-2}), as the reactor thermal power output per cm^2 of wall facing the plasma and, for our D-T reactor, include energy from Li^6 (n,t) reactions in the blanket. In the M.I.T. conceptual design, Homeyer[13] derives a maximum wall loading of 750 W cm^{-2}.*

8. Molybdenum is selected for the wall material facing the plasma, being chosen for its high temperature properties, low neutron capture and high neutron multiplication cross sections. The thickness (2 cm) of the single skin wall is determined by (i) thermal stress mainly from gamma radiation energy from the fused salt region, deposited in the wall, and (ii) mechanical stresses arising from immersion in the blanket salt. Homeyer's approximation for bremsstrahlung neglected the temperature dependency resulting in over-estimation of the radiation heat flux onto the wall. Also a thinner first wall would experience lower thermal stresses and could be incorporated in a double skin hollow wall system (of improved structural performance), the coolant flowing between the skins as well as outside the wall.

9. Taking this into account, we have estimated that the wall loading can be increased to 1300 W cm^{-2} of wall from all energy sources in a D-T fusion reactor. The rate of energy deposition in the walls at this wall loading is $\approx$ 250 W cm^{-2} of first wall.

Wall Radius

10. Having estimated a value for P_w we examine optimisation of the average fusion power density taken over the engineered volume of the fusion reactor. Using the notation given in Fig.3, the power density per unit volume is given by

$$P_D = \frac{2\pi \, r_w \, P_w}{\pi(r_w + t + s)^2} \text{ W cm}^{-3} \qquad \dots (1)$$

The value of $t + s$ can be taken as independent of r_w, since t is determined by the nuclear properties of the blanket and s is dominated by the thermal insulation surrounding the superconducting magnet windings. Hence simple differentiation shows the maximum value of the expression for P_D to occur when $r_w = t + s$. Homeyer[13] derives a value of 110 cm for the blanket thickness; allowing for additional nuclear shielding of the superconducting coils to reduce refrigeration costs,

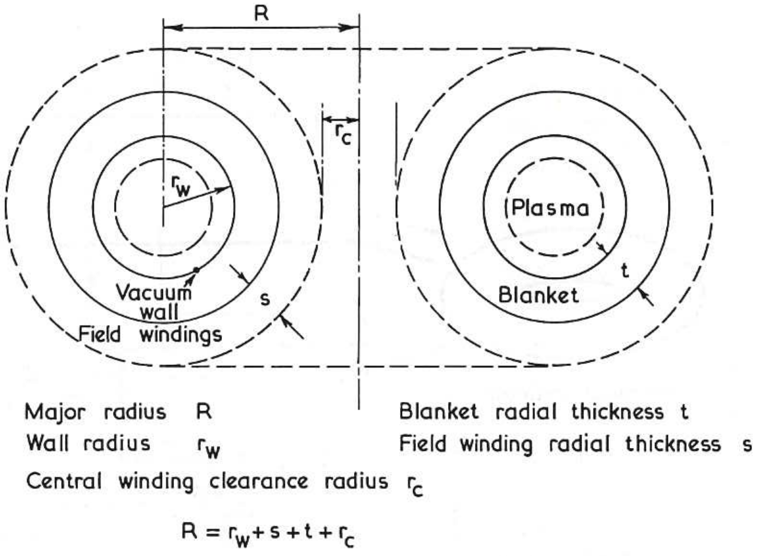

Fig.3 Diagram of fusion reactor in toroidal geometry (CLM-R85)

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*In reference 13, Homeyer defines power output of a fusion reactor in terms of a 'standard' source of 1 MW m^{-2} flux of 14 MeV neutron kinetic energy on the wall facing the plasma. He shows that the limit of his system is $\approx 5 \times$ 'standard' source, or $\approx$ 750 W cm^{-2}.

(see para.25) we take $t = 125$ cm. A tentative estimate for s of 50 cm therefore gives the value of r_w for optimum average power density as $125 + 50 = 175$ cm.

Reactor Average Power Densities

11. Using the values of r_w, s, t and P_w determined above, the average power density for our fusion reactor, $P_D \approx 3\cdot5$ Wcm^{-3}. As a guide to the economics of our new system, this can be compared with the power density of other advanced projects. A 1000 MW(e) fast breeder reactor design study[14] gives ratings of $2 - 2\cdot5$ Wcm^{-3} in the core-breeder assembly excluding the primary/secondary heat exchanger, circulating pumps and outer containment. Thus, with the above parameters our fusion reactor power density is of the right order of magnitude. The average power density over the volume inside the reactor wall is 21 W cm^{-3} and the required plasma power density, for a practical plasma radius must be $\approx$ 30 W cm^{-3}.

Reactor Output

12. We have assumed a toroidal system in which the maximum rated power output is given by

$$P_T = 4\pi^2 \, r_w \, R \, P_w \qquad \ldots (2)$$

P_T has a minimum value when $r_c = 0$ (see Fig.3) which, with $P_w = 1300$ W cm^2, $r_w = s + t = 175$ cm is $\approx$ 3100 MW(th). Assuming a thermal conversion efficiency η of 0.4, this is an electrical output from our fusion generating station of 1250 MW(e). The complication of designing a satisfactory magnet system with $r_c = 0$ would be clearly extreme and we have chosen a station size of 5000 MW(th) for our study. With $s = 50$ cm, this gives $r_c = 200$ cm and $R = 5\cdot5$ m. The aspect ratio, R/r_w, of the vacuum toroid for this reactor output is ≈ 3, about the minimum which appears practicable in toroidal form for the more complex forms of magnet system which are used in plasma confinement experiments.

13. Single generation units of this size – 5000 MW(th) and 2000 MW(e) – appear to be acceptable for electricity generation, depending on the size of the interconnected network used for electrical power distribution. Forecasts[14] for the U.K., Europe and United States are that by 1985 – 1990, generating units of 1500 – 2000 MW(e) will be required commercially, subject to no loss of reliability and continuation of the established trend of reducing capital costs per kW output with increasing unit size.

Magnetic Field Strength

14. Depending ultimately on the plasma physics requirements, we must estimate the value for B (the average magnetic field) outside the plasma in order to derive the containment parameters and the cost estimates. The nuclear power per cm length in cylindrical geometry, P_L is given by the proportionality:

$$P_L \propto \beta^2 B^4 r_p^2 \frac{\langle \sigma v \rangle}{kT^2} \qquad \ldots (3)$$

The last term is slowly varying over the range of kT of interest and, because of the B^4 term, the highest possible magnetic fields are often advocated[15]. However, P_w is defined by the reactor wall design and P_T by the toroidal geometry, the tritium breeding requirement (i.e. blanket) and choice of a commercially viable size for our reactor. Therefore P_L is itself defined and to utilise the B^4 dependency the other parameters must be changed to keep P_L constant*.

15. We choose superconductors for the field windings because, from estimates based on present technology (i.e. current densities and simple extrapolation of present production costs), they already appear the most economical (see para.26). Also with the negligible circulating power required for refrigeration, the use of superconductors will not affect the station net output. For the purpose of our reactor study, we have chosen $B = 100$ kG.

Plasma Density

16. The plasma density can be determined from the values of the engineering parameters, P_W and r_W, arrived at above. The nuclear power density in a reacting fusion plasma is given by

$$P_n = \tfrac{1}{4} n^2 Q_T \langle\overline{\sigma v}\rangle \times 1{\cdot}6 \times 10^{-16} \text{ W cm}^{-3} \qquad \ldots (4)$$

The nuclear power per centimetre length is given by

$$P_n \pi r_p^2 = 2\pi P_W r_W \qquad \ldots (5)$$

Combining these equations and substituting for Q_T (= 22·4 MeV for the D-T fusion reaction) we obtain

$$n = 1{\cdot}49 \times 10^6 \left(\frac{P_W}{\langle\overline{\sigma v}\rangle y^2 r_W} \right)^{\frac{1}{2}} \qquad \ldots (6)$$

where $y = r_p/r_W$. The plasma radius must be less than the wall radius and, taking $y = 0.7$ and $r_W = 1.75$ m, gives $r_p = 1{\cdot}25$ m and a plasma to wall clearance of 0·5 m. From this we can calculate n, knowing P_W and $\langle\overline{\sigma v}\rangle$. Clearly, with experience of plasma confinement in systems of these dimensions, a larger value of y might be used but in view of the uncertain performance of the confinement system we take the smaller rather than the larger value.

Plasma Power Balance - the Product 'nτ'

17. Lawson[16] has established necessary criteria for the containment parameter - 'nτ' - for a fusion power reactor from considerations of plasma power balance. Lawson's treatment is simple, assuming external heating of cold fuel to supply radiation, i.e. bremsstrahlung losses from the whole reacting plasma. The values for nτ derived are for zero net useful output, all output energy being used to heat the fuel at the high overall efficiency (including the thermal cycle efficiency) of $\eta\varepsilon = \frac{1}{3}$. We designate such a system as 'injection heated' and, in Appendix II, we have extended Lawson's treatment to cover the case of an economic injection heated fusion reactor. We show that nτ must be at least an order of magnitude greater than given by Lawson's analysis (see Fig.4).

18. The work of the Risö group reported by Kofoed-Hansen[17] extended Lawson's analysis. Accounting for both bremsstrahlung losses and in simplified terms for cyclotron radiation,

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*An alternative form of expression (3) is $P_L \propto \frac{\beta\, kT}{\alpha} B$. We have shown that P_L must be constant for a reactor of defined rating and under these circumstances this form shows more clearly the restriction on choice of magnetic field strength, B.

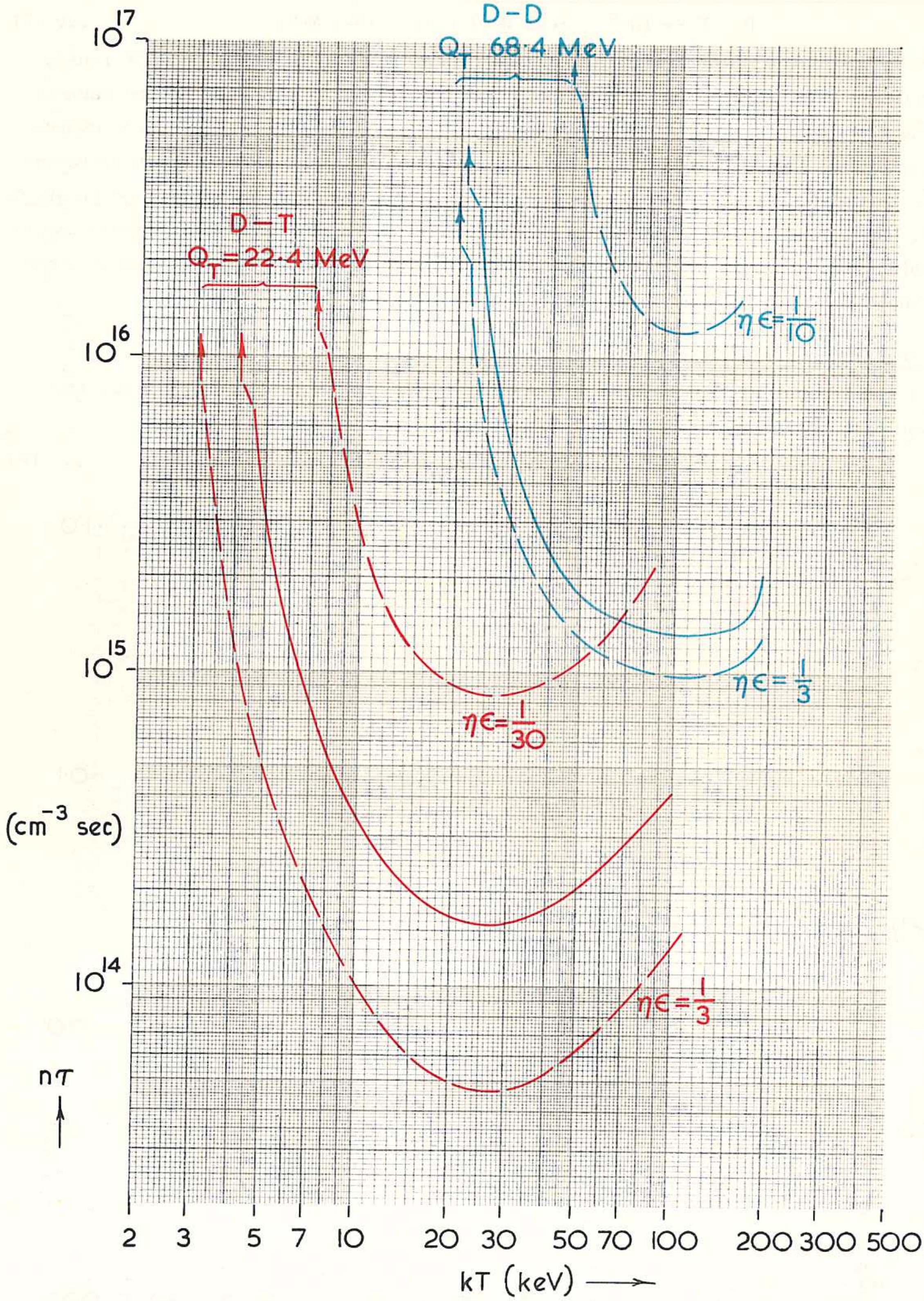

Fig. 4

(CLM-R85)

Curves of $n\tau$ as a function of kT (keV) for D-T and D-D reactors for injection heating at values of $\eta\epsilon$ shewn (dotted curves) and charged particle heating (solid curves.)

they also examine in more detail the alternative method of plasma heating in a steady-state system which we designate 'charged particle heating'. The fusion energy from the D-T reaction is divided between the reaction products according to the equation:

$$D + T \rightarrow (He^4 + 3{\cdot}52\ \text{MeV}) + (n + 14{\cdot}1\ \text{MeV}) \qquad \ldots (7)$$

Present theory indicates no preferential loss mechanism for the reaction product ions as compared with the fuel ions: the He^4 reaction products will be confined by the magnetic field. The Risö Group's study of energy exchange rates between the steady state components of the plasma shows that the He^4 ions become thermalised at the plasma temperatures needed in a toroidal system. Conditions for plasma power balance can be defined in which the initial energy of the He^4 ions alone is sufficient to supply the plasma losses and to heat new cold fuel. This is accomplished without the energy passing through a heat engine cycle and therefore with minimum losses.

Plasma Power Balance for Charged Particle Heating

19. In a simple analysis comparable to Lawson's treatment of injection heating, the plasma power balance condition is given by the equation

$$\tfrac{1}{4}\, n^2 \langle \overline{\sigma v} \rangle\, Q_c\, \tau \; - \; P_b \tau \; = \; 3\, n\, kT \qquad \ldots (8)$$

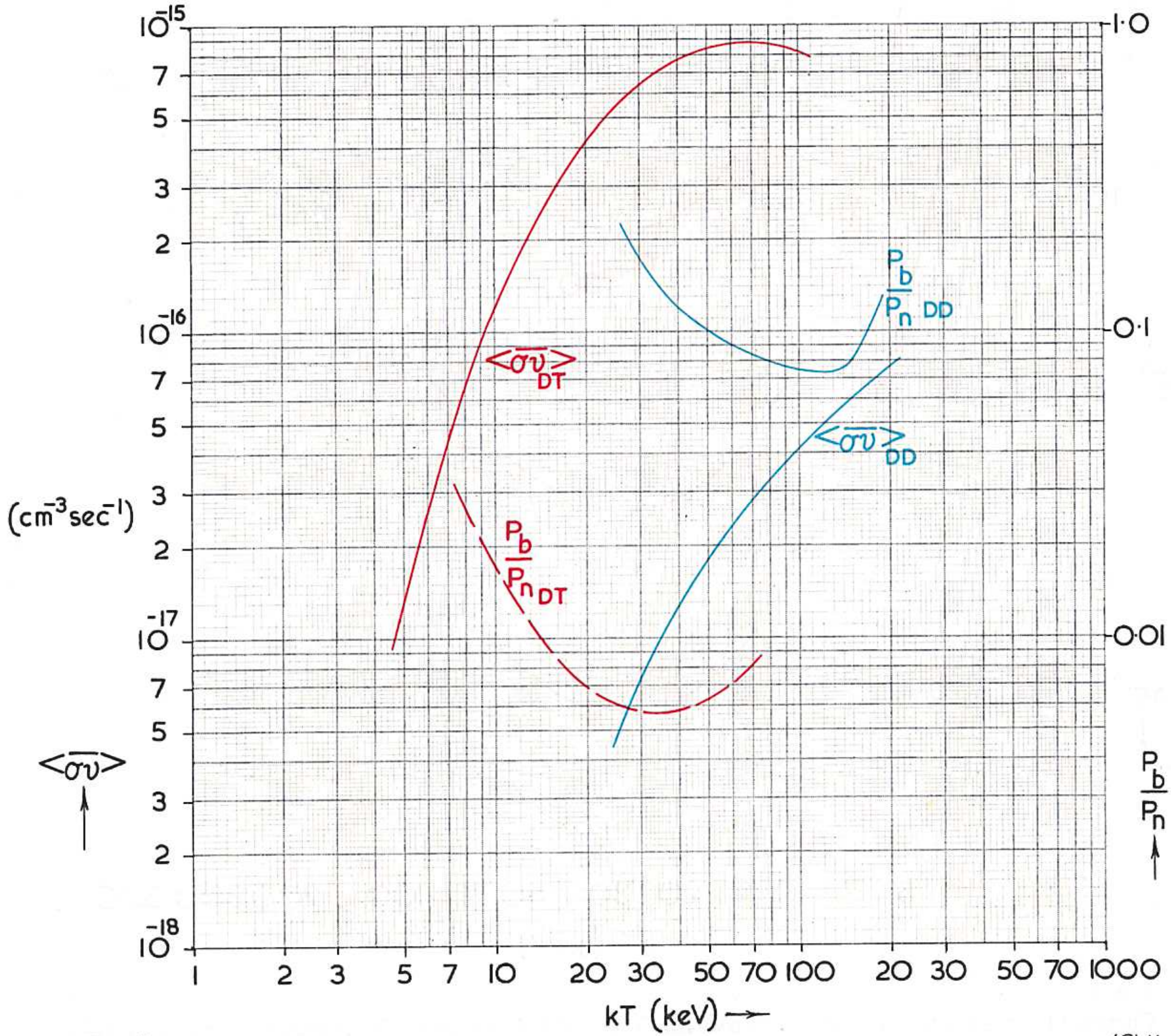

Fig. 5

Curves of $\langle \overline{\sigma v} \rangle$ the reaction rate parameter and P_b/P_n the ratio of bremsstrahlung to fusion power, as a function of kT (keV) for D-T and D-D fusion reactors with Li^6 and Na blankets, respectively. $Q_T = 22.4$ MeV for D-T. $Q_T = 68.4$ MeV for D-D (data from references 3 and 18).

The first term is the energy released by fusion to the charged reaction products and the second is the radiation loss term where

$$P_b = 5\cdot35 \times 10^{-31}\ \zeta\ (kT)^{\frac{1}{2}}\ n^2\ \mathrm{W\,cm^{-3}}$$

ζ being a correction factor for electron-electron bremsstrahlung[18]. At balance, the difference between these two terms must equal the energy to heat cold fuel supplied to the reaction volume, 3 nkT. This equation reduces to

$$n\tau = \frac{12\ kT}{Q_c\langle\overline{\sigma v}\rangle - 1\cdot34\ 10^{-14}\ \zeta\,(kT)^{\frac{1}{2}}} \qquad \ldots (9)$$

For the D-T reaction $Q_c = 3\cdot52$ MeV (see Eq.7) and using $\langle\overline{\sigma v}\rangle$ given in Fig.5, $n\tau$ can be calculated for chosen values of kT, the assumed plasma temperature. The result is the plot given in Fig.6 (Curve A). Curve B of Fig.6 is taken from the work of the Risö group. The close correlation between these two curves shows that our simple analysis is adequate at the present stage of fusion reactor studies.

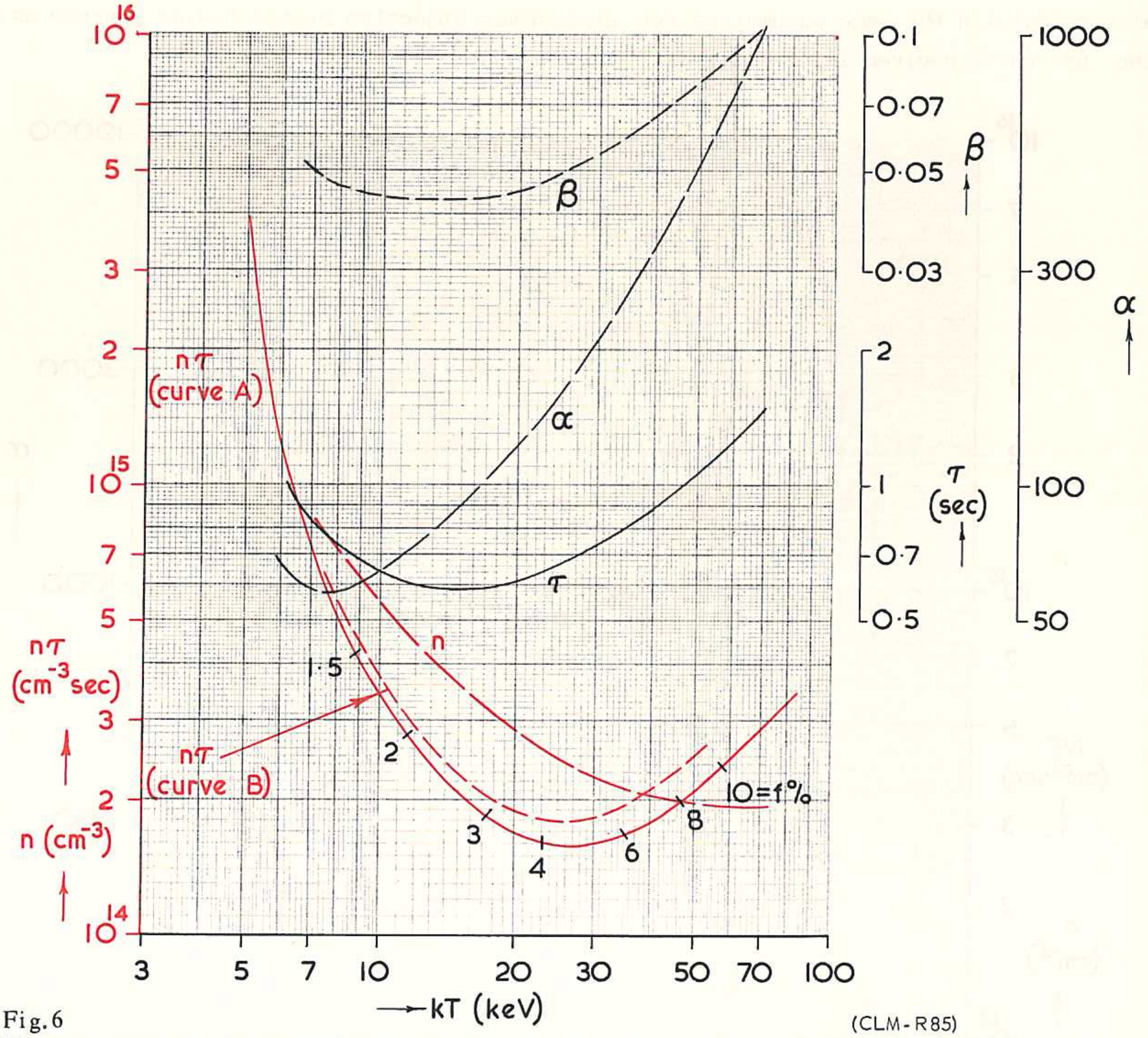

Fig.6 (CLM-R85)

Plasma parameters for charged particle heated D-T reactor as a function of kT (keV). $Q_T = 22.4$ MeV. $Q_c = 3.52$ MeV. B = 100 kG. $r_p = 1.25$ m. $r_w = 1.75$ m. $P_w = 1300\ \mathrm{W\,cm^{-2}}$. β shewn is not corrected for alpha particle pressure. $n\tau$, Curve A is from eq.4 and $n\tau$, Curve B is from Kofoed-Hansen.(17)

Containment Parameters

20. We can now derive the 'full power operation' containment time $\tau = \frac{n\tau}{n}$ for our D-T reactor where n is defined from the power density by equation 6. At reduced output, a different plasma power balance would be established which in all probability would have a lower n, and τ itself might have to be larger. The value of τ calculated as above is clearly only an indication of the system requirement. In any case, as suggested by Mills[19], it is improbable that a reactor design will produce exactly the right plasma containment time. The design will have to be capable of longer containment to permit control of operation at the required system τ, e.g. by spoliation of fuel or magnetic field or by change of fuel ratio by addition of hydrogen or excess deuterium. The remaining confinement parameters for our reactor are easily calculated, for B = 100 kG, from $\beta \left(= \frac{2\ nkT}{B^2/8\pi}\right)$ the ratio of plasma to magnetic pressure and $\alpha \left(= \frac{\tau}{\tau_B}\right)$ the ratio between τ and the Bohm diffusion time τ_B. Lastly, the percentage burn-up f can be calculated from the well-known relationship $f = \frac{1}{2}\, n\tau \langle\overline{\sigma v}\rangle \times 100$. These are shown for the Charged Particle Heated system in Fig.6 for values of kT between 7 and 70 keV. For comparison we have also calculated the same parameters for an economic Injection Heated fusion reactor using the $n\tau$ curve derived in Appendix II. (See Fig.7).

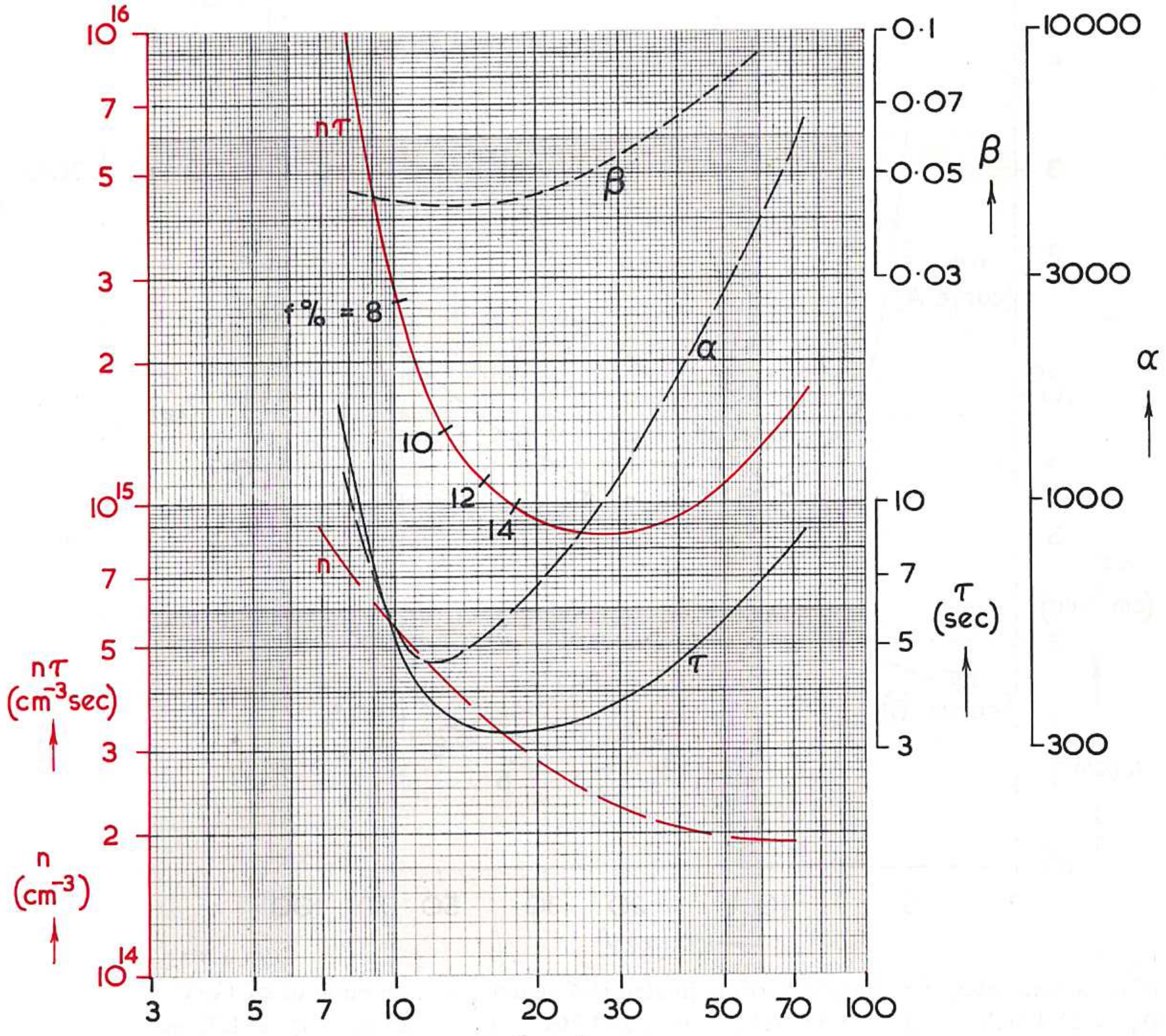

Fig. 7 (CLM-R85)

Plasma parameters for injection heated D-T reactor as a function of kT (keV). $Q_T = 22.4$ MeV. $\eta\epsilon = 1/30$. B = 100 kG. $r_p = 1.25$ m. $r_w = 1.75$ m. $P_w = 1300$ W cm^{-2}. β shewn is not corrected for alpha particle pressure.

21. For a Charged Particle Heated D-T reactor, Fig.6 shows that to operate at short containment times the plasma temperature should be between 10 to 20 keV with a preference for the higher temperature because of lower bremsstrahlung onto the wall (Fig.5). At 20 keV, n and $n\tau$ are relatively low, the burn-up not so low as to aggravate the tritium scavenging problem (para.33), β is close to its minimum value and the curve of the parameter α shows that the required containment is 120 times Bohm diffusion time.

22. In comparison, for the Injection Heated reactor, operation at 13 keV is indicated by Fig.7 though α must then be 470 and burn-up is increased to > 10%. The chosen data for both heating systems is given for comparison in Table I, with β corrected for the increased plasma pressure due to the average temperature of the alpha particles[20].

TABLE I

Containment parameters for D-T Reactor, 5000 MW (th)

Station Efficiency = 0·42. B = 100 kG
Plasma radius = 1·25 m.
Wall loading = 1300 W cm^{-2}.
Wall radius = 1·75 m

Item	Units	Plasma Heating	
		Charged Particle	Injection(1)
$n\tau$	cm^{-3} s	$1{\cdot}7 \times 10^{14}$	$1{\cdot}4 \times 10^{15}$
Temperature	keV	20	13
n	cm^{-3}	$2{\cdot}8 \times 10^{14}$	4×10^{14}
τ	s	0·6	3·5
τ_B	s	$4{\cdot}9 \times 10^{-3}$	$4{\cdot}9 \times 10^{-3}$
α	ratio τ/τ_B	120	470
β	pressure ratio	0·075(2)	> 0·043
Burn-up	fraction	0·035	> 0·10

Note (1) In the plasma energy balance, circulating power for injection heating ≈ 7%

(2) $\beta = 0{\cdot}045$ neglecting alpha particle pressure

23. Our simple analysis of power balance criteria for charged particle heating assumes that containment of all ionic species is the same and that Te = Ti : the more rigorous analysis referred to[17] shows that $1{\cdot}1 < Te/Ti < 1{\cdot}5$ between kT, 10 → 20 keV based on a 3-particle-group analysis of energy transfer. Also we ignore bremsstrahlung due to reaction products because burn-up is low. Cyclotron radiation losses calculated for our system according to the method of Rose and Clark[21] shows that $P_c \approx 0{\cdot}2\ P_B$ and this correction would slightly modify the simple analysis for power balance. It has already been noted that we choose superconducting coils for the magnetic field and their low refrigeration power requirements (Table IV) can be neglected in calculating plasma power balance. Similar assumptions are also made in deriving the parameters for injection heating (Appendix II and Table I). As indicated in Appendix II, the curve for $n\tau$ with $\eta\varepsilon = \frac{1}{30}$ is the lowest acceptable for our economic injection heated D-T reactor. To increase $n\tau$ at fixed kT, the containment time τ would have to be extended because n is determined by the upper limit of wall loading (equation 6).

4. COST ESTIMATE FOR D-T REACTOR

24. We have estimated the cost of a fusion power station based on the D-T reaction and charged particle heating (see Table I, third column). To derive costs in the usual units – £/kW(e) – we assume a net generation efficiency of 0·42 allowing 10% of the gross electrical output for auxiliary power supply to the fusion reactor and steam plant. This requires a gross thermodynamic efficiency ≈ 0·46, a figure already reported for a fission reactor design study[14], and we neglect any improvement which might be achieved in the future, e.g. by using a 'two fluid' cycle. The estimate for the steam cycle equipment is derived from contemporary fission reactor studies and, for the fusion plant, is based on estimates of material quantities with added fabrication and design cost allowances. For lack of design data, we can suggest only a very approximate cost for the fuel handling equipment. We have examined costs of fuel and the initial tritium supply to derive unit generation costs for D-T fusion electricity. The D-T power station estimate and unit generation costs are shown in Table II and the data for the estimates are discussed in paragraphs 25 to 33.

TABLE II

Capital and Generation Cost Estimate for 5000 MW (th) D-T Fusion Power Station. Output 2,100 MW(e).
Station efficiency = 0·42. Station power consumption ≈ 10%

(a) Capital Costs

Item	Cost £ / kW (e)	Remarks
Reactor Vessel & Blanket	4	
Superconducting Magnet	21.5	
Conventional Plant	29	
Reactor Auxiliaries	5 → 10	
Customer's 'on costs'	9 → 9.5	At 15%
TOTAL	68.5 → 74	

(b) Generation Costs

Item	Cost pence/kWh	Remarks
Capital Charges	0·21 → 0·23	8% interest, 25 yrs. life 80% load factor
Fuel	0·004	See Table VI
Operation & Maintenance	0·017	See fission reactor estimate (Table XI)
TOTAL	0·231 → 0·251	

Reactor Vessel and Blanket Costs

25. The reactor vessel and blanket costs are detailed in Table III. The graphite cost given is for Type EY9, a dense material specified for the U.K. Fused Salt Reactor. INOR-8 is a nickel base alloy containing 16·5% Mo, 7·5% Cr, 5% Fe, developed in U·S·A· for fused salt systems. The quantity of lead allows for additional shielding of the superconducting field coil as suggested by Homeyer[13]. The reduced nuclear heating of the coil lowers

refrigeration requirements and reduces total costs for blanket and magnet by about 10%. To allow for salt needed in heat exchangers, pumps and interconnecting piping, the amount of Li_2BeF_4 salt specified is double the quantity required for the blanket volume. Adding 25% to the cost of £1·95 × 10^5/metre length for design and contractor's 'on costs', gives a final cost of £4/kW(e) at a net efficiency of 0·42.

TABLE III

REACTOR VESSEL AND BLANKET COST ESTIMATE

MATERIAL	COST including fabrication £/lb	WEIGHT 10^3 lbs/ metre	COST/METRE LENGTH £ × 10^3
Mo	10·7	4·9	52.5
Graphite	0·95	5·9	5·6
Pb	0·053	120·0	6·4
LiH	3·57	6·2	22·1
INOR-8	1·6	16·2	26·0
Li_2BeF_4	1·43	57·0	82·0
			TOTAL 194·6

Reactor Vessel and Blanket Material Cost/Metre Length ...£195,000

Magnet Costs

26. Chester[22,23] has analysed costs of materials, fabrication, equipment (e.g. refrigerators) and power consumed, for a 50 kG magnet for a 1000 MW(th) MHD 'topped' power station and derived optimised conductor current densities for Cu (55 ^{o}K), Aℓ (20 ^{o}K), Na (8·5 ^{o}K) and NbZr (4·2 ^{o}K). Using his approach, we obtain the costs for a simple toroidal 100 kG magnet for the D-T reactor, as shown in Tables IV and V. Table IV details the costs for a superconducting magnet - in this case of Nb_3Sn because NbZr is not suitable for 100 kG working. Table V is a comparison of total annual costs for various conductors using optimum current densities derived by Chester to demonstrate the advantages of superconductors, even allowing the high material and winding costs used in Table IV.

27. The Nb_3Sn tape cost used for our estimate is based on quantity extrapolation of present production costs. It is still nearly two orders of magnitude above basic material costs and neglects any future improvement in critical current in superconductors. The winding cost (which includes all formers, insulation coolant channels etc.) is estimated at 10 times the winding cost for the same volume of copper coil, based on 'one off' costs. It includes also cost of coil protection and supply equipment, the former to dissipate 1000 MJ/metre of coil - the energy released by a superconducting to normal transition, and is a necessary allowance in view of the uncertainties of this new technology. In a fully developed fusion reactor, it is certain that extra windings not allowed for in Table IV will be required. The costs depend on the complexity of the magnetic field geometry used to achieve the required plasma confinement. Our choice of $B = 100$ kG may

TABLE IV

Estimated Capital Cost for Superconducting Toroidal 100 kG Magnet

minor dia. 6·2 m major dia. 11·1 m

Item	Cost / Unit	Cost/Metre length £ × 10^3	Remarks
Superconductor Nb_3Sn tape	£ 1 × 10^{-3} (A ft)$^{-1}$	520	Cost at present low production rate – £3·5 × 10^{-3} (A ft)$^{-1}$
Winding costs and insulation	10 × £ 25 per litre of superconductor tape	340	Cu coils cost £10/litre for transformer windings up to £25/litre for specials[23]. The factor (× 10) used includes allowance for coil protection equipment.
Refrigeration	15 kW from 4°K for whole coil	50	Total nuclear heating of coil – 10 kW. Heat gain through thermal insulation 1 Wm^{-2}: spare capacity allowed for = 30%
Thermal Insulation	£1000 m^{-2}	40	Large liquid He storage vessel cost £350 m^{-2} [23]
Magnet support	£ 3000 per ton	90	This is ≈ 4 times basic material costs for stainless steel – Chester suggests £1000 – 3000 per ton[23]

Magnet Cost/Metre length £1,040,000

(£21.5/kW(e) for our 5000 MW reactor)

(including 25% for contractor's 'on-costs' and η_{net} = 0·42)

TABLE V

Annual Cost Comparison/Metre Length for 100 kG Magnet

Material	Temperature °K	Current Density A cm^{-2}	Estimated Annual Cost £ × 10^3/metre length		
			Capital repayment 10% p.a.	Power including cooling at 0·25 d/kWh, 0·8 load factor	Total
Cu	328	600	53	200	253
Na	8·5	1000	88 – 161	36	124-197
Nb_3Sn	4	10^5	104	negligible	104

also be conservative: Fig.8 shows how costs decrease substantially with increased reactor rating for a Nb-Ti superconductor using present bulk production forecast costs. B could be reduced (for the same β) to 90 kG by reduction of plasma — wall clearance, i.e. $y = 0{\cdot}85$ in eq.6. At the present state of knowledge of superconductors and plasma confinement, we believe that our estimate incorporates sufficient margin for future problems of magnet construction and is not over-optimistic.

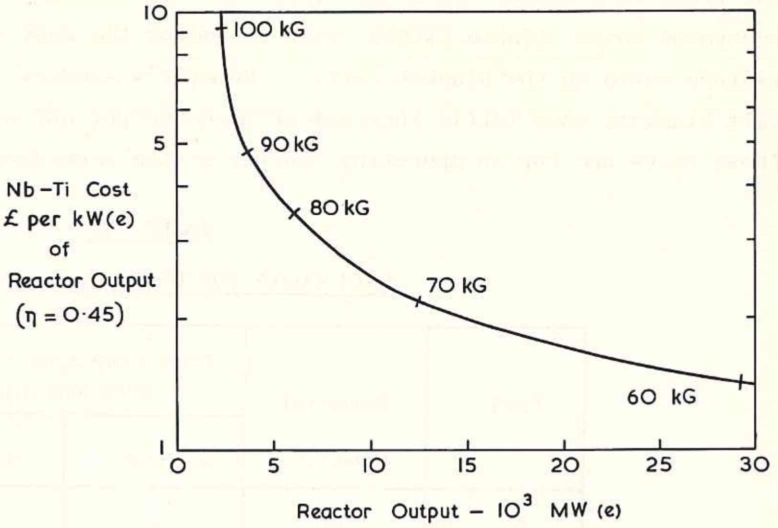

Fig.8 (CLM-R85)
Cost of Nb-Ti toroidal magnet as a function of fusion reactor output at constant β, i.e. $B_z^4 r_p$ = constant.

Conventional Plant Costs

28. 'Conventional Plant' is here defined as the remaining plant required to supply electrical energy to a transmission network, i.e. including the salt circulating pumps and all items from the heat exchangers to the station high voltage output terminal. Four different estimates giving breakdowns for first station designs for two British and two American reactor systems^{14,24,13,25}, were examined and compared. The steam conditions in all four are similar - 2400 psi, 560 °C, net efficiencies ≈ 0·43 - 0·44. The American studies include costs for molten salt primary circuits for energy input to the steam cycle. For comparison, these studies were normalised to the required unit size by the conventional ⅔ power cost law, and after allowances were made for the different design bases of each estimate, they agreed within 5%, giving a cost of £29/kW(e) for plant rated at 2250 MW(e) gross electrical output. This estimate is for a prototype station and does not include economies from replication and development. The close agreement between the four sets of data indicated sufficient accuracy for the present purpose.

Reactor Auxiliaries Costs

29. This is equipment for the reactor fuel supply and recovery i.e. injectors, divertors, tritium extraction and other auxiliaries in the salt system. Since charged particle heating is assumed, the injection equipment costs should not be excessive. Also noting that the fuel feed quantities are not immense (Table VI), the salt treatment and tritium recovery equipment costs are expected to be small, leaving as a major item of uncertainty the divertors for which no design data is available.

30. Tentatively a figure of £5 - 10/kW(e) is assumed as an allowance for these items and the cost of the initial tritium supply (see below).

D-T Fuel Costs

31. Appendix III gives data on prices and availability of thermonuclear fuels. The fuel consumption for a D-T reactor and current fuel prices are given in Table VI, assuming 100% recovery of unburnt fuel from exhaust plasma and a conversion efficiency of 0·42.

The gross fuel charge (0·004d/kW(e)) is clearly negligible in comparison with capital repayment costs (Table II(b)) even including the cost of Li^6 to maintain the natural isotope ratio in the blanket salt. Homeyer's studies[13] indicate that Li^6 enriched salt blankets show little increase of power output and would clearly raise fuel costs. These costs are for an operating reactor system providing its own tritium.

TABLE VI

Fuel Costs for D—T Fusion Reactor

Fuel	Material	Fuel Consumption for 5000 MW(th)		Cost
	pence / g	µg/kWh	kg/day	pence/ kWh × 10^3
D_2	15	8	0·43	0·120
Li^6	132	25	1·35	3·3
Li (natural)	2	2·8	0·15	0·006
Be	10	3·7	0·20	0·04

TOTAL = 0·0035d/kWh – say 0·004d/kWh

32. Initially, tritium from fission neutron irradiated lithium will be required at a price unlikely to change significantly in the future, of £1000/gram, (Appendix III). The first operating fusion reactor with a lithium blanket will be able to supply tritium at a price an order of magnitude less than this. To calculate the cost of the initial tritium supply for the first D-T reactor, accurate data on tritium solubility in all reactor materials under operating conditions (of temperature and pressure) is required. Using H_2 solubility data at a partial pressure of 1/10 atmosphere, the estimated quantity is 10 gram/m^2 of wall. This is 5 days consumption at full power from our assumed configuration or, at £1000/gram, an initial capital charge of £2/kW(e), 3% of the total capital cost (see Table II).

33. Solubilities are generally lower for tritium than for hydrogen and this estimate may be conservative. In addition to that held up in solution, the tritium inventory must include material circulating in the injection-extraction loop. At a daily tritium consumption of 650 g and a burn up of 0·035, the tritium mass flow in this loop will be 18·5 kg/day or 13 g/minute. Unless a very high gas efficiency is achieved in the injector, the greatest increase in the tritium inventory will be associated with the injector loop. For an order of magnitude estimate assume a gas efficiency of 0·01 and a 1 minute recirculation time. This results in an injector inventory of 1·3 kg. Thus the design of the whole tritium loop should be carefully chosen to balance plant costs against tritium inventory charges. If the tritium inventory can be kept small (of the order estimated) and processing is incorporated in the reactor auxiliaries, decay can be neglected as the tritium overall cycle time will be ≈ 1 week. Hence with a breeding gain as low as 0·02 – 0·03, a doubling time of ≈ 1 year can be obtained. Impink[12] has shown that gains $> 0·15$ can be achieved in 4π geometry. More compact blanket design and economies in tritium inventory and magnet costs will result from development of tritium processing technology.

5. D-T REACTOR WITH FISSILE BLANKET

34. Lontai has examined the use of fissile nuclides in a fusion reactor blanket[26]. He considers both Thorium^{232} and Uranium^{238} - natural materials with significant fast fission cross-sections. U^{238} is much superior to Th^{232}. The U^{238} bearing blanket finally developed in Lontai's study has a 1 cm thick Mo first wall cooled with non-fissile Li_2BeF_4 fused salt. The volume percent of salt and graphite in the primary alternator is the same as in Homeyer's blanket (79% salt 21% carbon) with the preferred fissile fused salt 23 mol percent $U^{238}F_4$, remainder LiF with 50% Li^6 enrichment. This configuration is calculated to give a tritium breeding gain ≈ 0·2 and has twice the thermal output of the non-fissile blanket. It produces one Pu^{239} atom for every five fusion neutrons reaching the vacuum wall, but the sum of the tritium and plutonium production rates is approximately constant so that for a specified tritium breeding gain, the plutonium production is fixed. The radial thickness of the fissile blanket is ≈ 50 cm for similar levels of neutron leakage to the outer coil shield as in the 65 cm thick non-fissile blanket, thus offering some possibility of a reduced overall blanket thickness. For a fissile blanketed D-T reactor of the same physical dimensions of vacuum wall and the same rating and order of cost as we have studied, the fusion power density would be half that of a reactor with a non-fissile blanket. Since $P_L \propto \beta^2 B^4$ for fixed r_p and kT, possible advantages of such a reactor could be:-

(i) An easing of the plasma containment parameters because at constant B, β could be reduced by 40%.

(ii) A reduction of the magnet costs because at the same β, B could be reduced to 85 kG. The reduced blanket thickness would also assist in this context.

(iii) Because the fusion power is halved, a reduction of divertor rating by 50% (and perhaps also costs by the same amount) and reduction of first wall damage.

35. Some penalties of this approach to a commercial fusion reactor are:-

(i) Additional radioactivity hazards, with higher safety and shielding costs and siting problems - offset in the future by expanding knowledge in these fields.

(ii) Increased fuel costs for enriched Li^6 and U^{238}.

(iii) Increased processing costs for removal of fission products from the primary attenuator fused salt.

6. THE D—D REACTOR

36. We have examined the D-D fusion reactor in steady state toroidal configuration using the analysis we have adopted for the D-T reactor. The D-D reaction rate parameters are given in Fig.4, assuming use of a sodium blanket to increase energy output by neutron capture. Using our simple analyses - equation 9, Q_C = 26·7 MeV for charged particle heating and equation II-3 (see Appendix II), Q_T = 68·4 MeV for injection heating, the $n\tau$ - kT curves have been included in Fig.4. The upper $n\tau$ curve is calculated for

injection heating $\eta\varepsilon = \frac{1}{10}$ but analysis of equation II-3 (see Appendix II), shows that there is a minimum value of $\eta\varepsilon = \frac{1}{14}$ (15% of output used for fuel heating) below which injection heating will not balance radiation losses. Unless means are found to reduce D-D reactor costs significantly below D-T costs, the injection heated D-D steady state system cannot compete economically with fission forecast costs.

37. The curve in Fig.4 for charged particle heated D-D plasma is optimistic – neglecting cyclotron radiation and bremsstrahlung from electron interactions with reaction products as can be seen by comparison with Fig.9 which gives the $n\tau - kT$ curve resulting from the more rigorous analysis by Kofoed-Hansen[17]. This shows that plasma power balance occurs and we have considered this system although the required containment is much harder to achieve than in the alternative D-T system. Table VII shows the energy release per fusion in the two fuel/blanket configurations. Compared with the 'D-T-Li' system at the same output, the 'D-D-Na' system results in an order of magnitude increase of bremsstrahlung on to the wall, but only half the neutron flux. The net effect is that in a D-D reactor, a 1 cm Mo first wall can be rated at about the same wall loading as we have used in the D-T reactor calculations. This assumes that gamma heating of the Mo wall is the same per incident neutron in the two systems and the use of a sodium salt coolant of properties similar to the Li_2BeF_4 salt used in the D-T reactor blanket.

TABLE VII

Energy Release per Fusion for D-D and D-T Charged Particle Heated Reactors

Energy Release as	D-D-Na Blanket per cent at 60 keV(1)	D-T-Li Blanket per cent at 20 keV(2)
Fusion neutrons	24	67
'Blanket' capture reaction	37	16
Bremsstrahlung to wall surface(3)	9	1
Plasma exhausted to diverters	30	16

NOTES: (1) Assumes 50/50 D-D branching ratio, Na neutron capture energy 12·6 MeV, and includes secondary plasma reactions. Neglects possible neutron multiplication gains and losses in blanket.

(2) Homeyer[13] calculates that in spite of neutron multiplication Li capture produces only 3·3 MeV per incident neutron on the first wall because of endothermic reactions and neutron losses - e.g. neutrons and gamma-rays absorbed in the coil shield account for 3% of the nuclear output.

(3) At $n\tau$ - kT of interest given in Table VIII.

38. A study of the sodium blanket system is required to establish wall loadings more accurately for the D-D reactor, but, in principle, the thickness of sodium blanket, coil shield and superconducting coils (B = 100 kG), place a similar limitation on the minimum size of the D-D reactor as for the D-T reactor (para.12) and hence at the same wall loading, the D-D reactor would operate at the same average power density.

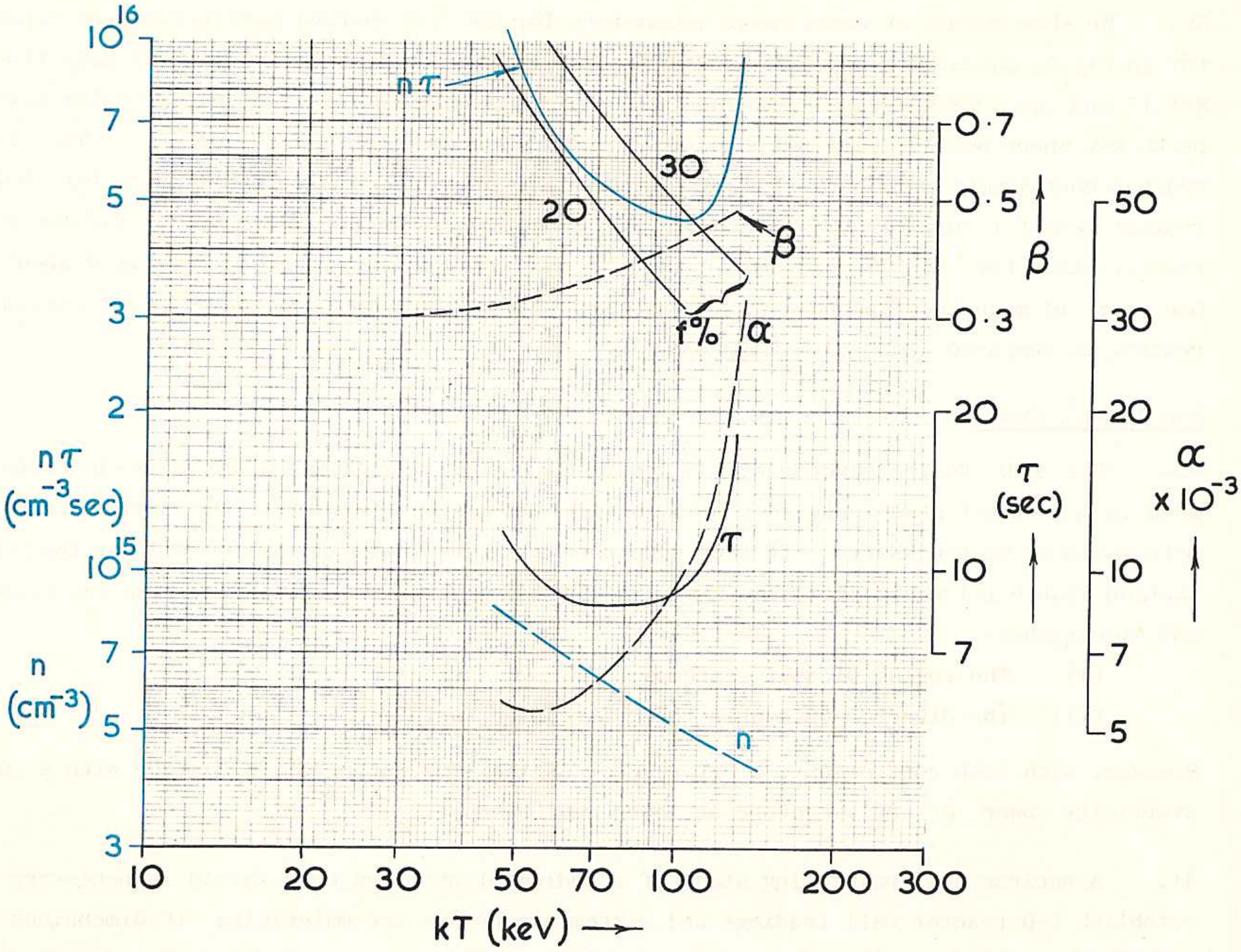

Fig. 9 (CLM-R85)

Plasma parameters for charged particle heated D-D reactor as a function of kT (keV). The $n\tau$-kT curve is from Kofoed-Hansen$^{(17)}$ and should be compared with solid curve for D-D (Fig. 4). $Q_T = 68.4$ MeV. B = 100 kG. $r_p = 1.25$ m. $r_w = 1.75$ m. $P_w = 1300$ W cm^{-2}. β shewn is not corrected for alpha particle pressure.

TABLE VIII

Comparison of Plasma Parameters for Charged Particle Heated D-D and D-T Reactors

Output 5000 MW(th), B = 100 kG   Plasma radius = 1·25 m
Wall loading = 1300 W cm^{-2} Wall radius = 1·75 m

Item	Units	D-D Reactor	D-T Reactor
$n\tau$	cm^{-3} s	$6{\cdot}3 \times 10^{15}$	$1{\cdot}7 \times 10^{14}$
Temperature	keV	60	20
n	cm^{-3}	$0{\cdot}7 \times 10^{15}$	$2{\cdot}8 \times 10^{14}$
τ	s	9·5	0·6
τ_B	s	$2{\cdot}0 \times 10^{-3}$	$4{\cdot}9 \times 10^{-3}$
α	ratio τ/τ_B	5500	120
β	pressure ratio	0·60$^{(1)}$	0·075$^{(1)}$
Burn up	fraction	0·22	0·35

NOTE: (1) β = 0·34 and 0·045 neglecting the pressure to contain reaction products.

The D-D Reactor Containment Parameters

39. We show curves of containment parameters for the D-D charged particle heated reactor in Fig.9, calculated as outlined for the D-T reactor, but using the $n\tau - kT$ data from Ref.17 and $Q_T = 68{\cdot}4$ MeV. From these curves, a possible choice of operating point might be 60 keV where burn up will not seriously aggravate bremsstrahlung losses. The D-D reactor containment parameters for this temperature are shown in Table VIII with the D-T reactor data for comparison. For these plasma parameters it can be shown, as for the D-T reactor, that for the D-D reactor, $P_c \approx 0{\cdot}1 \times P_b$ and can be neglected. Clearly about one order of magnitude increase in both alpha and beta would be required in a D-D fusion reactor as compared with its D-T equivalent.

D-D Reactor Costs

40. The D-D fusion reactor will be realised in the same geometry and magnetic field used in this short study only if plasma equilibrium can be achieved at the high value of beta shown to be necessary. If this should be so, the capital costs derived for the D-T station (Table II) would generally apply to the D-D reactor power station, with two principal exceptions:-

(i) The sodium blanket system.
(ii) The divertor of double the D-T reactor rating.

However, with such confinement, a D-T reactor of the same rating could be made with a substantially lower B and therefore at lower capital cost.

41. A nuclear and engineering study of a sodium blanket and coil shield is necessary to establish D-D reactor wall loadings and system dimensions and materials; if dimensions of the blanket can be reduced, this could materially affect magnetic field design and costs. Alternatively, shielding of the magnet may permit little alteration of dimensions of the whole blanket and cost per metre length of blanket and coil might change little for the two systems. Though clearly possessing greater potential for gain from direct conversion of the charged particle exhaust energy than the D-T system, the larger D-D system divertor rating may overall lead to increased cost/kW(e). Recovery of exhaust fuel (as opposed to 'exhaust' energy) need not be efficient since with no recovery and at 22% burn-up D-D fuel costs would be 0·0022 d/kWh, half the D-T costs given in Table VI. However, our knowledge of sodium blankets and divertors is insufficient to make a detailed comparison between D-D and D-T power costs.

7. FISSION AND FUSION POWER COSTS

Generation Costs

42. Weinberg[27] has shown that ultimately mankind must either 'burn the rocks' by fission breeding or 'burn the sea' by fusion to obtain his energy requirements. At the time of his forecast, neither the fission breeder nor the fusion containment problems had been solved. A prototype fission breeder power station (250 MW(e)) is now under construction in the U.K. and generating costs of 0·25 d/kWh from large base-load fission breeder power stations have been forecast for 1980-1990[28]. It is not a coincidence that the generation cost from our D-T reactor is of the same order. We derived an overall fusion reactor power density similar to the fission study forecasts and both forms of reactor require very

specialised technology, incurring similar costs. The cost of the remainder of the station must be similar because both reactors (fusion or fission) would drive the same type of heat engine-generator at a cost very roughly half the station capital cost.

TABLE IX

Comparison of Cost Estimates for Fusion Reactor Power Stations

		Capital Cost per kW(e)	Generating Cost d / kWh	Magnetic Field kG
Astron[7]	1958	-	0·5*	-
Stellarator[13]	1965	£ 58*	-	43
Stellarator[19]	1967	£ 40*	≈ 0·2	60
This report	1967	£ 68 - £ 74	0·23 - 0·25	100

* Converted to ground rules used in this report and station size of 2000 MW(e)

43. In Table IX we quote some other fusion reactor cost estimates which have been published. The significant difference between the three later estimates is the higher magnet costs derived in our work although in all three studies a simple solenoidal field system was assumed. This is partly accounted for by the difference in field strengths. Extrapolation of superconductor technology to the scale required by fusion reactors is extremely difficult: we anticipate, however, that our estimate is sufficiently conservative that, because of developments of superconductor production technology and magnet design and manufacture, the more complex field system required for a fusion reactor will not cost more that our figure of ≈ £ 20/kW(e). The development of superconductor technology is as vital to economic fusion power as is the control of plasma stability.

44. We estimate blanket costs for a D-T reactor as a small proportion of the total - £ 4/kW(e). Study of all relevant factors is important to maintain a high wall loading throughout the reactor life and thus not to exceed this estimate. Thinner blankets would reduce magnet costs, indicating scope for optimisation between these two cost elements. In addition to the sum in the magnet estimate for winding costs, we have included a significant item to cover reactor auxiliaries, divertor, and tritium recovery.

45. Comparing D-T and D-D systems, both require a blanket to utilise the neutron output and as a radiation shield for the magnet windings. Blanket and magnet systems for D-T or D-D reactors will probably be of similar size and both fusion processes will result in:

(i) very similar reactor configurations
(ii) costs sensitive to magnet costs
(iii) the same minimum size restriction in toroidal geometry.

The effect of this minimum size restriction on fusion reactors (para.12) would be reduced by combining electricity and water supply: extrapolating fission reactor desalination studies a 5000 MW(th) heat source would deliver ≈ 1500 MW(e).

46. Comparison of Tables II and XI shows that fusion energy costs are likely to be more capital-intensive than fission breeder energy costs. For the D-D-Na reactor, fuel costs

are clearly negligible. For the D-T reactor, tritium recovery processing must be incorporated in each reactor unit to obtain the low tritium inventory required. This has been allowed for in our estimate and thus the D-T reactor fuel costs based on current prices are also negligible. Clearly if fusion reactors can achieve cost parity with breeder fission reactors at ≈ 5000 MW(th), the scale of the enterprise above this level will always favour fusion power because of the higher fixed fuel charge in fission energy costs.

8. TECHNOLOGICAL PROBLEMS

47. Apart from the physics problems of containment, the feasibility of a D-T fusion reactor employing magnetic confinement depends on the solution of certain general technological problems. These fall into two categories, those determining the practicability of a fusion reactor and those important to its economic viability. In the former category we identify the vacuum wall, fuel injection and exhaust extraction, and starting the reactor; in the latter, tritium cycling and breeding, magnetic field production, direct energy conversion, and radiation damage in the structure.

The Vacuum Wall

48. The vacuum wall must be compatible with the requirements for heat transfer, plasma purity and neutron economy. These considerations dictate the following properties (at temperatures approaching 1000 °C):

(i) high mechanical strength
(ii) high thermal conductivity
(iii) low vapour pressure
(iv) resistance to corrosion by coolant
(v) low tritium hold-up
(vi) favourable neutron multiplication/capture probability
(vii) resistance to radiation damage.

Preliminary studies at M.I.T. favour a simple molybdenum wall[12,13] but a more complicated structure will be needed to increase the thermal loading to an economic level. Earlier suggestions that a molybdenum first wall would become surcharged with tritium, resulting in an unacceptable hold-up, can be discounted in the light of recent work[29,30]. Homeyer[13] has stressed the vital importance of radiation damage studies of first wall (and blanket) materials to permit realistic appraisal of fusion reactor potential.

Fuel Injection

49. The severe technological problems presented by the fuelling and exhaust requirements of a steady-state reactor have received little attention since the publication of the D stellarator report[31]. Our reactor with an output of 5000 MW(th) and 3·5% burn-up requires an injection rate of about 10^{23} atoms per second and a comparable exhaust flow; the sheer magnitude of the problem demands a radically new approach. Conventional injection techniques fall short by several orders of magnitude and, in addition, are much too inefficient for economic operation. The solution may lie in the development of cluster sources or other methods for the injection of 'fuel' pellets in the liquid or solid state.

Exhaust Extraction

50. Considerations of plasma purity and economic power density require that the charged reaction products and unburnt ions do not impinge on the vacuum wall but are chanelled into a divertor system. This must be capable of absorbing the exhaust power, which is 15% of the thermal output in the case of a D-T reactor employing charged particle heating, and must also permit tritium to be scavenged with great efficiency (para.33). The divertor will require considerable development as an item of some engineering complexity and high average power density.

Starting the Reactor

51. The method by which a steady-state reactor will be started up will depend largely on its magnetic topology and operating parameters, and consideration at this time must necessarily be highly speculative. It is worthwhile noting, however, that the problem is equivalent to one of making a pulsed D-T reactor which meets the Lawson break-even criterion in a physical and magnetic environment compatible with steady-state operation.

Tritium Cycling and Breeding

52. Three quantities are of crucial importance to the tritium economy of a fusion reactor:

(i) the breeding ratio - the number of tritium atoms produced in the blanket per neutron leaving the reacting volume;
(ii) the tritium hold-up - the equilibrium quantity of tritium present in the whole of the reactor outside the reacting volume;
(iii) the burn-up ratio - the fraction of the injected tritium which reacts per pass through the reacting volume.

The capital cost of the initial tritium supply is determined by the tritium hold up and the economics of all tritium processing equipment including the blanket. The mass flow will be minimised by operating at a high burn up ratio, but this limit is likely to be determined by the confinement system used, e.g. a low β leads to a low burn up.

53. Tritium breeding blankets have been studied in detail at M.I.T., but further work is needed to optimise the blanket configuration, for both non-fissile and fissile assemblies. Experimental results on a non-fissile blanket mock-up are in agreement with the calculated neutron spectra, but attempts to measure tritium production directly have not yet been successful[28].

54. The estimates of the likely tritium hold-up in a reactor are largely guesswork. Owing to the lack of data on the solubility of tritium in the structural materials[33] the results are uncertain to an order of magnitude. Much work remains to be done here. The methods to be used to recover bred tritium from the blanket and unburnt tritium from the exhaust have received little attention. Although no serious obstacles are expected, the demonstration of a satisfactory system is desirable.

Magnetic Field Production

55. The required field strength and volume (100 kG and 1000 m^3) will clearly extend present magnet technology. Since the magnetic topology of a practicable containment

system cannot yet be specified, we can only draw general conclusions under this heading, indicating current limitations and areas ripe for technological investigation:

(i) Maximum fields obtainable[34]

The strength of existing materials limits the value of steady magnetic fields to ≈400 kG for resistive conductors. If superconducting coils are used, the properties of superconducting materials so far studied restrict the field to ≈ 220 kG.

(ii) Economics of large solenoids

Further to the analysis in para.26, we have estimated the effect of reducing the confining magnetic field to take advantage of the superconductor characteristic (current density scales as B^{-1}). Reduction of B to 90 kG shows a magnet cost reduction of ≈ 20%, i.e. to ≈ £ 17/kW(e), but to maintain the required plasma parameters (β constant) the reactor size is increased and output is 7500 MW(th). Lower material costs and increased current density superconductors for 100 kG fields are important developments for fusion power exploitation.

(iii) Complex coil system

Supporting the additional coils required for high-shear systems will present severe mechanical problems. A preliminary appraisal of a high-shear stellarator reactor[35], for example, calls for an 'ℓ' winding carrying 8×10^7 A in an ambient field of 200 kG, which would require restraint forces of 7×10^6 pounds per inch of conductor length. The solution of such problems may lie in the development of whisker-reinforced high strength materials.

Radiation Damage

56. It is important that the structural integrity of the reactor be preserved throughout its useful life. Evaluation of the seriousness of radiation damage to the reactor structure is hampered by lack of data on the effects of 14 MeV neutron fluxes $\approx 10^{15}\ s^{-1}\ cm^{-2}$. It is to be expected that both displacement and transmutation effects will be relatively more important than in the case of fission reactors. There, neutron energies of ≈ 2 MeV are encountered and those portions of the reactor most likely to be damaged by high energy neutron fluxes are designed to be replaced during normal refuelling.

Direct Conversion

57. It is possible in principle to convert the charged particle component of the fusion energy directly into electrical energy with an efficiency approaching unity. This would have the effect of increasing the conversion efficiency of the reactor; using our design parameters, the maximum possible increase is from 0·45 to 0·54 for D-T and to 0·61 for D-D. This is a worthwhile improvement, since station running costs are inversely proportional to conversion efficiency if fuel costs are negligible. Three methods of direct conversion can be envisaged:

(i) cyclic variation of the plasma pressure and volume[36]

(ii) utilisation of the exhaust of unburnt fuel and charged reaction products;

(iii) charge separation derived from the high birth-energy of the charge reaction products.

Feasibility studies are required, followed by the development of the most promising approach.

Sodium Blankets

58. The power balance for a D-D system, (para.37) assumes that all neutrons leaving the plasma are captured in sodium, releasing the capture energy of 12·6 MeV. Technological studies are required to establish the feasibility of such a blanket and to optimise its thickness; any significant reduction in the latter would reduce the magnet costs.

9. CONCLUSIONS

59. We have estimated containment parameters (see Table X) which on the basis of present technology, must be satisfied if economic electricity generation from thermonuclear fusion is to be achieved.

TABLE X

Fusion Reactor Containment Parameters

Plasma	Fuel	Heating	$n\tau$ $cm^{-3}s$	Temperature keV	B = 100 kG	
					α	β
D-T	D , Li^6	Injection	$1{\cdot}4 \times 10^{15}$	13	470	0·043
D-T	D , Li^6	Charged Particle	$1{\cdot}7 \times 10^{14}$	20	120	0·075
D-D	D,Na	Charged Particle	$6{\cdot}3 \times 10^{15}$	60	5500	0·60

60. On the basis of current plasma confinement studies, we have postulated a D-T fusion reactor in toroidal geometry. The requirement to breed tritium and the use of superconductor field coils defines the minimum blanket thickness and hence the system scale length is about 1m. The economic output is critically determined by the technology of wall and blanket design; our estimated maximum wall loading is 1300 W cm^{-2}. These engineering parameters determine the minimum economic rating of a toroidal fusion reactor. From our study, we arrive at a D-T reactor rating of 5000 MW(th) for which, coupled to conventional energy conversion plant ($\eta_T = 0{\cdot}42$) we estimate unit generation costs of 0·23 - 0·25 pence/kWh, about the same as fission reactor forecasts for 1980 - 1990. The older technology of conventional plant and the new technology of superconductors are very significant factors in fusion power and fusion-fission cost comparisons.

61. Using charged particle heating, the technological requirements of a D-D reactor are not significantly greater than for a D-T reactor. However, plasma instabilities must be controlled to give a 50-fold improvement in containment over D-T requirements and this must be at beta an order of magnitude greater, (Table X above). An economic D-D charged particle heated reactor would be about the same size and rated output as the D-T reactor, though this anticipates the results of sodium blanket studies not yet reported. In broad terms, the cost of D-D fusion power could be similar to D-T.

62. A 5000 MW(th) D-T reactor with a fissile blanket (U^{238}) could be operated at half the fusion power density of one without a fissile blanket and could offer some economic advantages at the expense of fission problems.

63. Important areas for study and development engineering necessary for commercial exploitation of thermonuclear fusion are:

(i) Economic optimisation of blanket configurations for the non-fissile and fissile D-T and D-D fusion systems, including the effects of blanket thickness on magnet costs together with studies of all the technological aspects of blankets (e.g. heat transfer, nuclear reactions, radiation damage, mechanical stresses and corrosion) to determine 'whole-life' economic wall loadings for fusion reactors.

(ii) Development of low cost, large and probably complex field systems, at B of the order of 70 - 120 kG, using superconductors which are essential for economic fusion power.

(iii) Methods of 'cold' fuel injection and 'hot' ($\geqslant$ 10 keV) exhaust to process of the order of 10^{23} atoms s^{-1} at high gas and energetic efficiencies.

(iv) Tritium processing equipment to reject helium and recover tritium from the exhaust fuel and the breeding blanket.

(v) Starting a steady state fusion reactor.

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APPENDIX I

COST OF CAPACITOR ENERGY STORAGE FOR PULSED REACTORS

REACTOR PARAMETERS

1. We assume a reactor of cylindrical geometry, in which a D-T plasma is contained by a pulsed magnetic field derived from a capacitor bank, with the following specification:

Capacitor cost	X pence per joule stored C £ per kW(e) of reactor output
Capacitor life	Y pulses
Pulse repetition frequency	$\nu\ s^{-1}$
Reactor life	L years
Magnetic field energy	W_M erg cm^{-1}
Thermonuclear energy released per pulse	W_T erg cm^{-1}
Thermal efficiency	η_T

COSTING EQUATIONS

2. The cost of the capacitors is thus

$$(W_M \times 10^{-7})\ \frac{X}{240}\ (3{\cdot}16 \times 10^7)\ \frac{L\nu}{Y}\ \text{£ cm}^{-1}$$

and the electrical power output is

$$(W_T\ \nu\ \eta_T) \times 10^{-10} \qquad \text{kW(e) cm}^{-1}$$

Hence the contribution of the capacitors to the capital cost is

$$C = \frac{W_M\ X\ L}{W_T\ Y\ \eta_T}\ (1{\cdot}3 \times 10^8) \qquad \text{£ per kW(e)} \qquad \ldots \text{(I-1)}$$

3. The important ratio W_M/W_T can be expressed in terms of the usual plasma parameters. If r_w is the wall radius and r_p the initial radius of the plasma,

$$W_M > \frac{B^2}{8\pi}\left[\pi(r_w^2 - r_p^2) + (1 - \beta)\ \pi r_p^2\right] \text{ erg cm}^{-1}$$

$$> \frac{2nkT}{\beta}\left[\pi(r_w^2 - \beta r_p^2)\right]$$

If a fraction f of the D-T mixture is consumed in each pulse,

$$W_T = \pi\ r_p^2\ \tfrac{1}{2}\ n f Q_T \text{ erg cm}^{-1}$$

Thus

$$\frac{W_M}{W_T} > \frac{4\ kT}{f\ Q_T}\left[\frac{r_w^2}{\beta\ r_p^2} - 1\right] \qquad \ldots \text{(I-2)}$$

ESTIMATES OF W_M/W_T

4. Optimistic. Ribe[15] proposes a $\beta = 1$ system heated by alpha-particles. During the pulse, the plasma expands to a radius r_f, given by

$$\frac{r_f^2}{r_p^2} = 1 + \frac{f\ Q_c}{10\ kT} \qquad \ldots \text{(Ribe's eq.17)}$$

since $r_w > r_f$ we have

$$\frac{r_w^2}{r_p^2} - 1 > \frac{f\ Q_c}{10\ kT}$$

Substituting in equation (I-2) gives

$$\frac{W_M}{W_T} > \frac{4}{10}\frac{Q_C}{Q_T} \qquad \text{... (I-3)}$$

Taking, as Ribe does, $Q_C = 3{\cdot}5$ MeV and $Q_T = 18{\cdot}9$ MeV, we have

$$\frac{W_M}{W_T} > 0{\cdot}075$$

5. Realistic. Roberts and Thonemann[37] suggest that power loading on the walls restricts the plasma radius to about one twentieth of the wall radius. Thus equation (I-2) becomes:

$$\frac{W_M}{W_T} > \frac{1600}{\pounds}\frac{kT}{Q_T},$$

so that even for 50% burn up and kT as low as 10 keV

$$\frac{W_M}{W_T} > 1{\cdot}8 \ .$$

COST ESTIMATES

6. Taking these two values of W_M/W_T as extremes, equation (I-1) gives a cost range

$$C = \frac{X\,L}{Y\,\eta_T}\,(0{\cdot}1 \quad \text{to} \quad 2{\cdot}3 \times 10^8) \qquad \pounds \text{ per kW(e)}$$

Energy storage capacitors with a life of 10^6 pulses now cost 3d - 6d per joule, and we assume a reactor life of 20 years and $\eta_T = 0.4$. This gives C = £1,500 to £70,000 per kW(e), that is, twenty to one thousand times the acceptable capital cost of the whole station .

LONG-LIFE CAPACITORS

7. We now consider using capacitors whose life exceeds that of the reactor. Assuming an acceptable mean wall loading of P_W W cm^{-2}:

$$\text{electrical power} = 2\,\pi\,r_w\,P_W\,\eta_T \ \text{W cm}^{-1}$$

$$\text{capacitor cost} = (W_M \times 10^{-7})\,\frac{X}{240}\ \pounds\ \text{cm}^{-1}$$

where

$$W_M > \pi r_W^2 \cdot \frac{B^2}{8\pi}\ \text{erg cm}^{-1}$$

Hence

$$C > \frac{X\,r_W\,B^2}{P_W\,\eta_T(1{\cdot}2 \times 10^8)} \quad \pounds \text{ per kW(e)} \qquad \text{... (I-4)}$$

Taking $\eta_T = 0{\cdot}4$, $P_W = 1000$ W cm^{-2} , $r_W = 100$ cm and B = 100 kG , values which are reasonable and self-consistent, we obtain

$$C > 20\,X \quad \pounds \text{ per kW(e)}$$

8. Capacitors with a 30 year life now cost £2 to £3 per kVA at 50 Hz; in terms of energy storage this is about 10/- per joule. Thus C > £2400 per kW(e) which is again prohibitively expensive, by more than two orders of magnitude.

CONCLUSION

9. The excessive capital cost of capacitative energy storage precludes its use for providing pulsed magnetic containment in a fusion power station, and it fails by so large a margin that no conceivable development can alter the situation. Clearly we must look to other means of storing energy for this purpose.

APPENDIX II

PLASMA POWER BALANCE FOR AN ECONOMIC INJECTION HEATED FUSION REACTOR

POWER BALANCE EQUATION

1. In Lawson's simple treatment[16], fuel is injected into the reaction space with energy in excess of the plasma thermal energy, $3\,n\,kT$, to supply bremsstrahlung radiation losses P_b during the reaction time τ. Other losses are neglected. The thermonuclear reaction output – $\frac{1}{4}\,n^2 \langle\sigma v\rangle Q_T\tau$ – and the injected energy are all assumed recovered with overall efficiency $\eta\varepsilon$ where ε is the fraction of output used for preheating fuel at overall efficiency η. The condition for plasma power balance is that these are equal – i.e.

$$3\,n\,kT + P_b\tau = \eta\varepsilon\left(\tfrac{1}{4}\,n^2 \langle\sigma v\rangle Q_T\tau + 3\,n\,kT + P_b\tau\right) \qquad \text{... (II-1)}$$

The overall plant efficiency η is the product of the thermal conversion efficiency η_T and the injector efficiency η_I. The radiation term P_b is given by

$$P_b = 5{\cdot}35 \times 10^{-31}\,\zeta\, n^2\,(kT)^{\frac{1}{2}}\ \mathrm{W\ cm^{-3}} \qquad \text{... (II-2)}$$

where ζ is a correction for electron-electron bremsstrahlung[18]. Equation II-1 reduces to

$$n\tau = \frac{12\ kT}{\frac{\eta\varepsilon}{1-\eta\varepsilon}\,Q_T\langle\sigma v\rangle - 1{\cdot}34\times10^{-14}\,\zeta\,(kT)^{\frac{1}{2}}} \qquad \text{... (II-3)}$$

For a lithium blanketed reactor burning equal parts of deuterium and tritium, the reaction rate parameter is given in Fig.5 and $Q_T = 22{\cdot}4$ MeV. With this data, curves of $n\tau$ as a function of kT can be drawn for different values of the product $\eta\varepsilon$. Lawson assumed that $\eta = \frac{1}{3}$ and using $\varepsilon = 1$, obtained the well-known Lawson criterion for zero net power output from a fusion reactor. (See Fig.4, page 7). A fusion reactor for electricity generation based on this criterion is useful only for a feasibility demonstration of thermonuclear power.

ECONOMIC INJECTION HEATED REACTOR POWER BALANCE

2. To obtain $n\tau$ as a function of kT for an economic injection heated fusion reactor, we must determine values for η and ε. By definition an economic fusion reactor must generate electricity at no greater cost than any other system, e.g. the generation costs forecast for a British Sodium Cooled Fast Reactor Station (circa 1980) and shown in Table XI. Low fuel costs are forecast for fusion power. We derive costs $< 0{\cdot}004$ d/kWh (see paras. 31 and 41) which is negligible in comparison with the estimated fast breeder fusion reactor fuel costs of 0·066 d/kWh. Justified partly by the fact that thermal cycle plant and operating costs will be very similar in both systems, we assume that the capital and operating costs/kWh for our fusion station are the same as the fast breeder estimate. Therefore we can use the savings on fuel costs to pay for any increase in reactor and plant rating to supply preheating energy. This will allow a maximum circulating power fraction given by

$$\varepsilon = \frac{\text{fuel savings/kW(e)}}{\text{generation costs/kW(e)}}$$

or

$$\varepsilon = \frac{0{\cdot}066 - 0{\cdot}004}{0{\cdot}264} \approx 0{\cdot}23\ .$$

TABLE XI

Estimated Generation costs from Fast Breeder Reactor[14] — 2 × 1000 MW(e) Station – circa 1980 – Gross output 2 × 1046 MW(e)

Item	Cost pence/kWh Note (a)	Note (b)
Capital charges	0·203	0·181
Operation, Maintenance and Insurance	0·018	0·017
Fuel charges (insensitive to primary uranium costs)	0·072	0·066
Generation costs pence/kWh	0·293	0·264

NOTES: (a) For a single station, excluding economies from replication and resale of plutonium, and related to U.K. conditions. (Ground rules used in Ref.15, 20 year life, 0·75 load factor 7½% interest.)

(b) To the ground rules used in this report, i.e. 25 year life, 0·8 load factor and 8% interest.

3. We neglect the possibility of direct conversion of fusion energy for which $\eta_T = 1$. As defined, η is given by the product of η_T (the station thermal efficiency) and η_I the injection equipment energetic efficiency. Advanced cycle thermal efficiencies of $\approx 0{\cdot}55$ have been forecast e.g. for the potassium/steam two fluid system. Using superconductors for the ion source focusing fields, present 'neutral injection' equipments could operate at $0{\cdot}02 < \eta_I < 0{\cdot}05$. Assuming an improvement on the upper figure by $\times 5$, $\eta_T \times \eta_I = 0{\cdot}55 \times (5 \times 0{\cdot}05) = 0{\cdot}137$, and with $\varepsilon = 0{\cdot}23$ $\eta\varepsilon = 0{\cdot}033$. The corresponding $n\tau - kT$ criterion is given by the upper curve for D-T injection heating in Fig.4. Even this $n\tau - kT$ criterion may be too low because ε has been determined only for economic parity with the fission reactor and η_I as deduced may be optimistic. We conclude that $n\tau$ for an economic injection heated D-T fusion reactor must be at least an order of magnitude above the Lawson criterion.

APPENDIX III

THE PRICE AND AVAILABILITY OF THERMONUCLEAR FUELS

FUEL SUPPLIES

1. Deuterium is plentiful and cheap, and reserves are inexhaustable. The current price for heavy water is $29·5 per pound, and it is expected to fall to ≈ $16 per pound. Present supplies of tritium are manufactured by fission neutron irradiation of lithium. Hence it is expensive, and the production required for the initial inventory is in kilogram quantities (1 kg ~ 10 megacuries) and would be a major undertaking. The estimated price for quantity production of 'fission' bred tritium is £1000 per gram whilst fusion reactor tritium costs would be an order of magnitude lower. Fortuitous sources of tritium, such as heavy water used as a fission reactor moderator, do not yield sufficient tritium to be of interest for fusion purposes.

BLANKET MATERIALS

2. Supplies of beryllium and lithium seem to present no immediate problem; the average content of the earth's crust is 65 grams of Li and 6 grams of Be per tonne[38] (for comparison, the lead content is 16 grams per tonne). The annual production of both in U.S.A. is equivalent to a few thousand tons of metal, and the bulk price quoted for Li_2BeF_4 is $4 per pound. Sodium is abundant, and the current price for metal of reactor coolant quality is £120 per ton, or 15 cents per pound.

WORLD RESERVES

3. A comparison of the energy potential of the estimated terrestrial reserves of uranium, thorium and lithium shows that from the point of view of long term fuel supplies, there is little to choose between fission and D-T reactors. Table XII gives figures recently quoted by McKelvey and Duncan[39]. The values are in units of Q(= 10^{18} Btu); in the case of uranium and thorium, breeding, i.e. 100% utilisation, is assumed; the lithium values are based on the consumption of the Li^6 content (7·4%) in a D-T reactor,

TABLE XII

Energy Content of World Fusion Fuel Reserves

	Uranium	Thorium	Lithium
	Q	Q	Q
At current prices (High grade ores)	76	48	18(a)
Estimated reserves (Low grade ores)	5×10^6	7×10^6	5×10^6 (b)

NOTES: (a) Current demand is small, and this figure is very conservative

(b) Excluding Li^6 content of oceans, estimated to be 6×10^6 Q.

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